The soil was assumed to be homogeneous and isotropic. The van Genuchten relationship was used for the moisture retention curve, while the Brooks Corey relationship was used to define the relative permeability function.

Modeling Approach and Results

The PCG4 solver was selected to solve the system of matrix equations with a convergence tolerance of 0.01 cm. An initial time step size of 0.01 days was enlarged by a factor of 1.2 up to a maximum time step size of 0.05 days. Computed values of hydraulic head along the base and top of the flow region are plotted in Figure 2.B2 for a time value of 0.508 days. These results compare very well with results obtained by using the finite-element model of HydroGeoLogic (1992).

2.3C VERIFICATION EXAMPLE FOR AIR-PHASE FLOW SIMULATION

The air-phase flow simulation option of the BCF4 package is verified by comparing numerical results with those obtained by using a comprehensive multi-phase flow simulator (Huyakorn et al., 1994).

The problem considered here is detailed by Panday et al. (1994). This problem was selected to study the flow dynamics of an air-sparging process. Relevant field site information given by Marley and Magee (1992) is used for this study. The site of concern has been contaminated by gasoline from several leaking underground storage tanks in both the vadose and saturated zones. The average depth to the water table is ~2.4 m below land surface. The contamination covers an area of ~450 m^2. A preliminary assessment of the sparging influence radius and air velocities in the vicinity of an injection well may be obtained by considering variably saturated air flow only (i.e., assuming passive liquid phases). A rectangular domain of 30 m × 20 m × 3 m was considered and discretized into 900 nodes having uniform nodal spacings of Δx = 2m, Δy = 2m, and Δz = 0.5m. The initial conditions correspond to prevailing atmospheric pressure in the vadose zone ($h_{a\Phi}=0$). The sparging process was created by injecting air at a steady rate of $10^{-3} m^3 s^{-1}$ at the node located at x = 9 m, y = 9 m, and z = 0.75 m. The water table is located 0.4 m below the sparging well (i.e., at z=0.35). Atmospheric pressure conditions were maintained on the surface boundary throughout the simulation and the bottom and lateral boundaries were treated as no-flow conditions. The soil and fluid properties used in the simulation were adopted from values given by Marely and Magee (1992) and are shown below.

Saturated hydraulic conductivity, K	=	3.92×10^{-8} m/s
Specific yield (i.e., porosity), S_y	=	0.35
Specific storage, S_s	=	3.53×10^{-5}
Water density, ρ_w	=	1,000 kg m^{-3}
Water viscosity, μ_w	=	0.5 cP
Water compressibility, β_w	=	10^{-8} Pa^{-1}
Air density, ρ_a	=	1.777 kg m^{-3}
Air viscosity, μ_a	=	$0.1983\cdot10^{-4}$ cP
Air compressibility,	=	$1.777\cdot10^{-5}$ Pa^{-1}
Residual water saturation, S_{wr}	=	0.40512
van Genuchten α	=	0.145 m^{-1}
van Genuchten β	=	2.7
Standard atmospheric pressure, P_{atm}	=	1.01×10^{5} Pa
Gravitational acceleration, g	=	9.8066 m/s^2

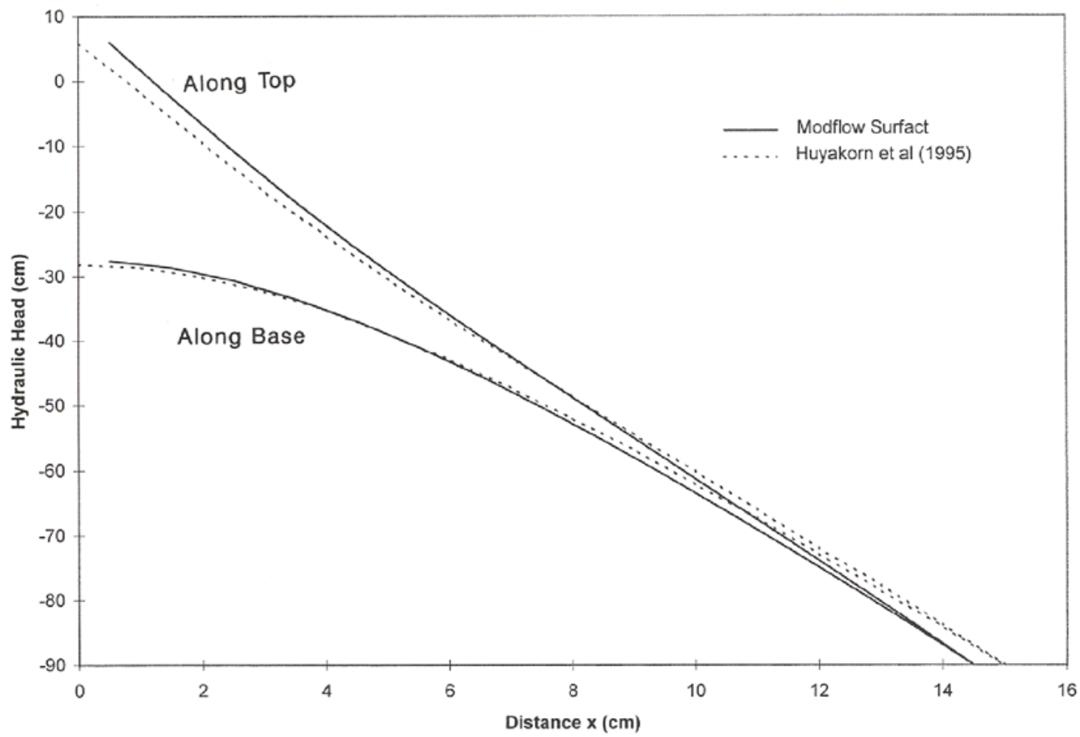

Figure 2.B2 Hydraulic Head Profiles at .508d for Flow in an Unsaturated Rectangular Soil Slab.

The van Genuchten functions were used to describe the relative permeabilities and capillary pressure of the air-water system.

Modeling Approach and Results

Both transient and steady-state simulations were performed for this problem. Transient simulations invoked the AT04 package for adaptive time stepping with an initial time step size of 1 sec, a minimum $\Delta t = 1 \times 10^{-3}$s, maximum $\Delta t = 1 \times 10^{5}$s, a time step multiplier of 1.4 and a time step reduction factor of 2. The PCG4 package was selected to solve the system of matrix equations with a maximum of 20 non-linear iterations for the transient case and 100 non-linear equations for the steady-state simulation. Head closure criteria were 0.1 and 0.21 m for the transient and steady-state simulations, respectively.

The simulated distributions of air pressure along a horizontal line through the well are depicted in Figure 2.C1 for both simulations along with simulations using the finite-element code of Huyakorn et al. (1994) at t=7 min, and at steady-state conditions. The predicted and observed pressure profiles are in reasonable agreement with both codes. It is interesting to note that the transient simulation reaches steady-state conditions in only 1.16 days showing the rapid equilibration process that occurs in the air phase. Absolute air pressures for these simulations were computed from the potentiometric head by equation (22) with ρ_a calculated from equation (23).

2.4 APPLICATION EXAMPLES

Two example problems are provided to demonstrate the application of the variably saturated flow option of the new BCF4 Package. In both examples, sufficient pumping is allowed to occur to desaturate portions of an unconfined aquifer. The first example is a steady-state pumping simulation. The second example is a transient simulation in which the wells are shut off after a four-year stress period to rejuvenate the aquifer. This scenario is also modeled using the existing wetting option in MODFLOW (McDonald et al., 1991) and the STAFF3D finite-element code (HydroGeoLogic, Inc., 1992). The results obtained from different methods are compared and discussed below.

2.4.1 Problem 1—Steady-State Simulation of Pumping in an Unconfined Aquifer

This test problem considers a 300-ft thick unconfined aquifer shown in Figure 2.2. The modeled domain is a square of dimensions 75,000 ft H 75,000 ft. The top and bottom of the aquifer are at elevations of 50 and –250 ft, respectively. The domain is subject to a uniform and continuous vertical recharge of 3.0 H 10^{-9} ft/s. The left (west) boundary in the figure is a constant head boundary, and the remaining boundaries are no-flow boundaries. Fifteen wells, screened over 100 ft of the bottom of the aquifer are each pumped at a rate of 0.95 ft^3/s. The locations of wells are shown in Figure 2.2. Aquifer parameters include:

Horizontal hydraulic conductivity, K_h (K_{xx} *and* K_{yy})	=	10^{-4} ft/s
Vertical hydraulic conductivity, K_v (K_{zz})	=	10^{-5} ft/s

Modeling Approach

The domain is uniformly discretized into 3 layers, 15 rows, and 15 columns of grid blocks (i.e., Δz = 100 ft, $\Delta x = \Delta y$ = 5,000 ft). Thus, the value of *VCONT* (vertical hydraulic conductivity divided by inter-layer distance between two adjacent nodal layers) is calculated as $10^{-7}s^{-1}$. A constant head of zero is prescribed on the west side of top and middle layers. The initial head distribution required by the code is